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Strategic Resource Allocation in the Human Brain Supports Cognitive Coordination of Object and Spatial Working Memory

Margaret C. Jackson,[1]* Helen M. Morgan,[1] Kimron L. Shapiro,[1] Harald Mohr,[2] and David E.J. Linden[1]

[1]*School of Psychology, Bangor University, Bangor, United Kingdom*
[2]*Johann Wolfgang Goethe University, Frankfurt, Germany*

Abstract: The ability to integrate different types of information (e.g., object identity and spatial orientation) and maintain or manipulate them concurrently in working memory (WM) facilitates the flow of ongoing tasks and is essential for normal human cognition. Research shows that object and spatial information is maintained and manipulated in WM via separate pathways in the brain (object/ventral versus spatial/dorsal). How does the human brain coordinate the activity of different specialized systems to conjoin different types of information? Here we used functional magnetic resonance imaging to investigate conjunction- versus single-task manipulation of object (compute average color blend) and spatial (compute intermediate angle) information in WM. Object WM was associated with ventral (inferior frontal gyrus, occipital cortex), and spatial WM with dorsal (parietal cortex, superior frontal, and temporal sulci) regions. Conjoined object/spatial WM resulted in intermediate activity in these specialized areas, but greater activity in different prefrontal and parietal areas. Unique to our study, we found lower temporo-occipital activity and greater deactivation in temporal and medial prefrontal cortices for conjunction- versus single-tasks. Using structural equation modeling, we derived a conjunction-task connectivity model that comprises a frontoparietal network with a bidirectional DLPFC-VLPFC connection, and a direct parietal-extrastriate pathway. We suggest that these activation/deactivation patterns reflect efficient resource allocation throughout the brain and propose a new extended version of the biased competition model of WM. *Hum Brain Mapp 32:1330–1348, 2011.* © 2010 Wiley-Liss, Inc.

Key words: working memory; conjunction; visuospatial; fMRI; SEM

INTRODUCTION

Working memory (WM) serves to maintain and manipulate information over a period of a few seconds when perceptual input is temporarily absent, and thus facilitates the flow of ongoing tasks [Baddeley and Hitch, 1974]. For example, the ability to maintain a mental representation of object form enables a coherent and stable picture of the visual contents of our environment [Phillips, 1974]; the ability to manipulate incoming information and transform it into another related form, such as the mental rotation of objects, allows us to track changeable aspects of an often dynamic world.

Baddeley and Hitch's [1974] original three-component model incorporates a central executive (CE) system that

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*Correspondence to: Margaret C. Jackson, School of Psychology, Bangor University, Bangor, Gwynedd LL57 2AS, United Kingdom. E-mail: m.jackson@bangor.ac.uk

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acts as an attentional control center, and fractionates WM into two "slave" systems according to the type of information that is processed: visuospatial WM and verbal WM. This distinction is garnered from behavioral studies that showed little dual-task cost when two concurrent tasks recruited different WM systems (i.e., verbal and visuospatial) but larger dual-task cost when use of the same WM system was required (i.e., visuospatial and visuospatial). Subsequent studies have provided additional support for this theory [e.g, Cocchini et al., 2002; Logie et al., 1990]. Behavioral evidence for further fractionation of visuospatial WM into separate object identity and spatial location systems has also been found [e.g., Della Sala et al., 1999; Finke et al., 2005; Klauer and Zhao, 2004]. The most widely cited evidence for separate object and spatial WM systems is provided by functional imaging studies that found distinct involvement of different brain regions for object and spatial WM tasks, known as the "domain-specific" account. Object WM tasks involving object identification have been shown to preferentially activate ventral processing pathways (e.g., ventrolateral prefrontal cortex; VLPFC), whereas spatial WM tasks have been shown to preferentially activate dorsal processing pathways (e.g., dorsolateral prefrontal cortex; DLPFC) [Haxby et al., 2000; Sala et al., 2003; Ungerleider et al., 1998]. In addition, transient disruption of ventral and dorsal prefrontal regions using transcranial magnetic stimulation (TMS) has been shown to result in temporary impairments in object and spatial WM, respectively [Mottaghy et al., 2002]. Although the majority of spatial WM studies have investigated memory for object location, spatial properties inherent to objects, such as angle and orientation, have also been shown to recruit the dorsal pathway during WM [Mohr et al., 2006; Rothmayer et al., 2007].

An alternative model of WM architecture defines the role of ventral and dorsal prefrontal regions according to maintenance and manipulation processes respectively, known as the "process-specific" account [D'Esposito et al., 1998, 1999; Nystrom et al., 2000; Owen et al., 1998, 1999]. Yet evidence exists that both WM maintenance and manipulation of spatial properties (orientation) and object properties (color) are associated with a dorsal-ventral gradient of cortical activation [Mohr et al., 2006]. Volle et al. [2008] provide additional support for this multifunctional role of lateral PFC in which both domain- and process-specific functions coexist [see also Courtney, 2004; Postle, 2006].

Many everyday tasks involve a combination of WM processes. For example, we commonly need to remember not only the identity of an object but also its concurrent location or orientation in space. If WM is fractionated, how do we combine different forms of information that are processed in separate brain regions in order to create an integrated representation in WM?

While most previous functional imaging studies of WM integration have focused on maintenance activity, in this article we investigate for the first time how resources are allocated throughout the whole brain when both object/ventral and spatial/dorsal information has to be manipulated and integrated in WM.

Several neurophysiological studies have investigated the effects on WM performance of maintaining conjunctions of spatial and nonspatial information compared to maintenance of each component alone. Two key findings have emerged: (1) domain-specific brain regions that reflect separate WM processes are also recruited for integrated tasks, but integration-related activity is intermediate to that elicited by the preferred and nonpreferred single-task information (object and spatial location WM: [Munk et al., 2002; Sala and Courtney, 2007]); (2) Integrated versus separate WM processes recruit additional regions of the frontal cortex (object and spatial location: [Mitchell et al., 2000; Munk et al., 2002]; verbal and spatial location: [Prabhakaran et al., 2000]) that are argued to be involved in executive processes.

Here we ask whether similar results will arise when integrated information has to be manipulated as opposed to simply maintained. On the basis of a previous behavioral study [Mohr and Linden, 2005], participants performed object (compute average color blend) and spatial orientation (compute intermediate angle) WM manipulation tasks separately or in conjunction during functional magnetic resonance imaging (fMRI). Possible predictions were as follows: (1) the same brain regions would be active during both single and conjunction tasks but conjunction-task activity would be (a) lower than, (b) higher than, or (c) intermediate to preferred single-task activity; (2) conjunction-task trials would elicit activity in additional brain regions that are recruited to a lesser extent during either of the single-tasks. Manipulation of information in WM is thought to rely on greater central executive resources than maintenance operations [Mohr and Linden, 2005], and Mohr et al. [2006] have shown evidence of this with higher activity in the frontoparietal network during WM manipulation versus maintenance. We therefore might expect that the integration of manipulated information will further add to the drain on executive resources and result in higher conjunction- than single-task activity in PFC and parietal regions.

MATERIALS AND METHODS

Subjects

Twenty healthy volunteers (mean age 25 years; 10 females; 19 right-handed) from the student and community panels of the School of Psychology, Bangor University participated in return for £20. Two subjects were excluded from this experiment due to excessive head movement inside the scanner, yielding a sample size of $n = 18$. Subjects reported no history of neurological or psychiatric disorder had normal or corrected to normal vision, and provided informed consent prior to participation. The study was approved by the School's ethics committee.

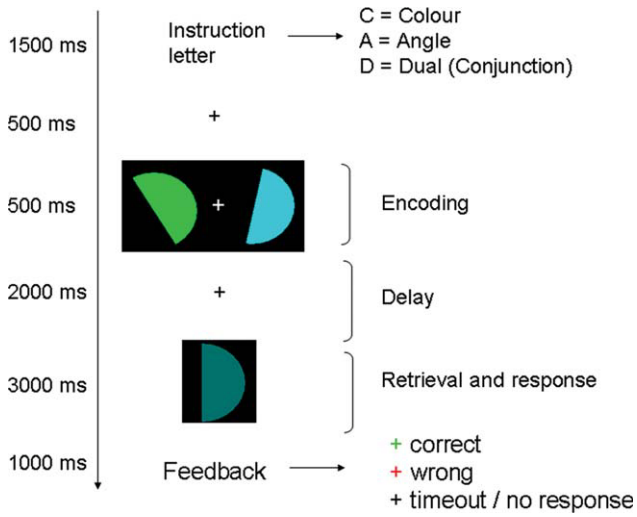

Figure 1.
An example trial procedure.

Stimuli

We used colored semicircles that varied in hue (defined in Hue Saturation Value (HSV) color space and represented by 0–360°) and the angle of the straight edge. Each item subtended approximately 2.2° × 4.1° and separated center to center by 7.6°.

Procedure

We used a WM manipulation task in which subjects were required to manipulate color and angle information, either separately or in conjunction, from pairs of colored semicirlces. Subjects computed either the average color blend

(color only task), the intermediate angle (angle only task), or both color and angle (conjunction task). Figure 1 illustrates an example trial. A trial began with the central presentation of a cue letter for 1,500 ms, designating what information was to-be-remembered. Cue letters "C," "A," and "D" signaled that subjects were to remember color only, angle only, or both color and angle (conjunction task), respectively. After a 500-ms fixation cross interval (this cross remained on screen throughout the trial with instructions to maintain fixation), two differently colored and angled semicircles were presented for 500 ms in the center of the computer screen ("sample display"). During this encoding phase, the two semicircles always differed in hue by 60° and in angle rotation by 60°. There were always two stimuli on screen on every trial (WM load 2). After a 2,000-ms memory retention interval ("delay") during which the items disappeared from view, subjects were presented with a single probe semicircle in the center of the screen ("test display"), to which they responded "yes" or "no" depending on whether they thought this single item represented the exact color blend, intermediate angle, or both, of the previous item pair. The single probe remained on screen for 3,000 ms, during which subjects were to respond with a simple button press, using their right and left hand for each response. Responses were counterbalanced such that half of the subjects used their right hand to respond "yes" and remaining subjects used their left hand for this response. The probe remained on screen for 3,000 ms regardless of participants' response time. After the probe disappeared, subjects received feedback via the reappearance of the central fixation cross which was colored green for correct, red for incorrect, and gray for no/late response (present for 1,000 ms). The cross returned to black and the next trial began. The intertrial interval (ITI) varied between 4.5 and 11.5 s (average ITI was 7.5 s). In each condition, the probabilities of match ("yes" response) and mismatch ("no" response) trials were 33% and 66%, respectively. On single-task match trials, the rotation angle/hue of the single probe stimulus was intermediate to each of the two sample stimuli, differing 30° from each. On color mismatch trials (66%), the hue of the single probe stimulus differed from the correct intermediate hue by either 50° (50%) or 30° (50%), angle always mismatched. On angle mismatch trials (66%), the angle of the single-probe stimulus differed from the correct intermediate angle by 20° (50%) or 30° (50%), color always mismatched. On color match trials (33%), color always matched and angle always mismatched. On angle match trials (33%), angle always matched and color always mismatched. On conjunction-task match trials (33%), both color and angle matched exactly the intermediate manipulation of the preceding two sample items. On conjunction-task mismatch trials, only one property was mismatched to the sample by the degrees outlined above for single trials (33% of trials were color mismatch; 33% of trials were angle mismatch). This design and the uneven distribution of match and mismatch trials were chosen to prevent participants from focusing on one dimension exclusively during the conjunction task, a method used in Mohr and Linden [2005].

In an event-related design, 60 experimental trials were presented for each condition (colour, angle, conjunction) in a pseudorandom order, resulting in 180 trials in total. To minimize subject fatigue, the experiment was separated into four separate scan runs comprising 45 trials each, within a single scanning session. Each run lasted approximately 11 min. Before the main experiment began, subjects were given a short practice session outside the scanner.

As this is the first investigation of neural responses to conjunction-task costs during WM manipulation, our aim in this study was to provide an initial examination of overall conjunction-task effects on WM without separating the task into encoding, delay, and retrieval. To separate these components a much longer delay interval is required between each stage. Previous research using a conjunction-task shape and color WM paradigm has shown that longer WM delay intervals elicit greater brain activity in some areas and reduced WM accuracy and response time than

shorter delays [Picchioni et al., 2007], suggesting that the delay interval can modulate WM resource allocation strategies. At this stage in the research, we felt it more prudent to use an established short-delay paradigm to assess conjunction-task resource allocation.

Data Acquisition

Behavioral data were acquired with a computer running DOS. The tasks were generated by the ERTS (Experimental Run Time System, Berisoft, Frankfurt, Germany) software. fMRI data were acquired with a Philips 3.0T MRI scanner with a SENSE parallel head coil. We used a gradient echo echoplanar sequence sensitive to the blood oxygen level dependent (BOLD) signal (TR = 1,000 ms; TE = 30 ms; matrix size = 80 × 80; FOV = 240 × 240 mm^2; voxel size = 3 × 3 × 3 mm^3; 65° flip angle; 17 axial slices; 5 mm slice thickness with 0.5 mm slice gap). Two dummy volumes were acquired before each scan block to reduce possible T1 saturation effects. During the WM task, the fMRI sequence was synchronized with the presentation of the cue letter at the start of each trial. Anatomical data were acquired with a high resolution T1-weighted three-dimensional (3D) volume (1 × 1 × 1 mm^3) and used for coregistration of functional data.

Data Analysis

Behavioral data analysis

To provide a sensitive measure of response, we converted hits and false alarm rates into *A*-prime (*A*′)[1]. The hit rate is the probability of "yes" responses when the probe represented the exact intermediate color, angle, or both color and angle of the preceding pair of images; the false alarm rate is the probability of "yes" responses when the probe did not match the preceding pair. These data were subjected to a repeated-measures analysis of variance (ANOVA) with task (color, angle, conjunction) as a within factor, and post-hoc paired samples *t*-tests (significance values were Bonferroni corrected for multiple comparisons).

Functional data analysis

Functional data were preprocessed and analyzed using the BrainVoyager 1.79 software (Braininnovation, Maastricht, The Netherlands). We applied slice scan time correction using sinc interpolation, 3D motion correction using trilinear interpolation, spatial smoothing (8 mm Gaussian kernel), and a temporal high-pass filter (low frequency cut-off: 3 cycles per run). 3D anatomical scans were transformed into Talairach space [Talairach and Tournoux, 1988], the parameters of which were applied to the coregistered functional data to yield 3D functional volumes ("volume time courses").

In total, 72 z-normalized volume time courses were entered into a whole brain, random effects GLM. The GLM had 18 (number of subjects) × 3 (conditions) = 54 predictors. We computed three contrasts: color minus angle to determine color-preferred regions; angle minus color to determine angle-preferred regions; conjunction minus color and conjunction minus angle conjunction analysis to determine whether additional areas are recruited for conjunction versus single tasks. Significance levels for the color and angle single task analyses were set at false discovery rate (FDR) < 0.05. For the conjunction-versus single-task analysis, to reduce the probability of false negatives while still reducing false positives, we corrected for multiple comparisons by using cluster-size thresholding [Forman et al., 1995; Goebel et al., 2006] for which we set a corrected significance threshold of $P < 0.05$ (FWHM = 2.66; no mask applied). The minimum cluster size used for the threshold was 108 voxels. For each of the thus identified regions of interest (ROI), we extracted beta values using ROI analysis and computed paired-samples *t*-tests on these values to compare all experimental conditions (alpha levels reported are Bonferroni corrected for multiple comparisons). We adopted this approach because this is the preferred and more stringent method based on a whole-brain analysis. However, we also applied a random effects repeated measures analysis of variance (ANOVA) model to our data and computed a main effect of task to determine any further task-modulated regions of interest. The ANOVA confirmed all regions identified in the whole-brain approach, and contrasts between conditions (conjunction vs. angle, conjunction vs. color, angle vs. color) computed for these regions produced the same results as the whole-brain contrasts reported in detail later. We present main effects of color, angle, and conjunction tasks in Supporting Information Figure S1. These flatmaps show that the task was associated with largely overlapping activity in visual, frontal, and parietal areas as demonstrated before for object and spatial memory tasks [Munk et al., 2002], reflecting the fact the stimuli were physically identical and many task components (visual processing, attention, executive control, response preparation) were shared by all conditions. However, over and above this, the task-specific contrasts that we observed are of interest because they are most likely to be associated with the specific processes for each individual condition (spatial transformation for angle, colour transformation and object memory for color, cognitive coordination for conjunction).

Furthermore, to examine how well the group results reflect processes at the individual level, we plotted each participant's BOLD response using beta values from each task contrast output (see Supporting Information Fig. S2: single-task regions, and Supporting Information Fig. S3: conjunction-task regions). This confirmed that the majority of subjects showed the effects found at group level.

[1] $A' = (0.5 + ((\text{Hits} - \text{False alarms}) \times (1 + \text{Hits} - \text{False Alarms}))/((4 \times \text{Hits} \times (1 - \text{False alarms}))$. When the false alarm rate is greater than the hit rate, the *A*′ formula used is: $(0.5 - ((\text{False alarms} - \text{Hits}) \times (1 + \text{False alarms} - \text{Hits}))/((4 \times \text{False alarms} \times (1 - \text{Hits}))$ [Grier, 1971].

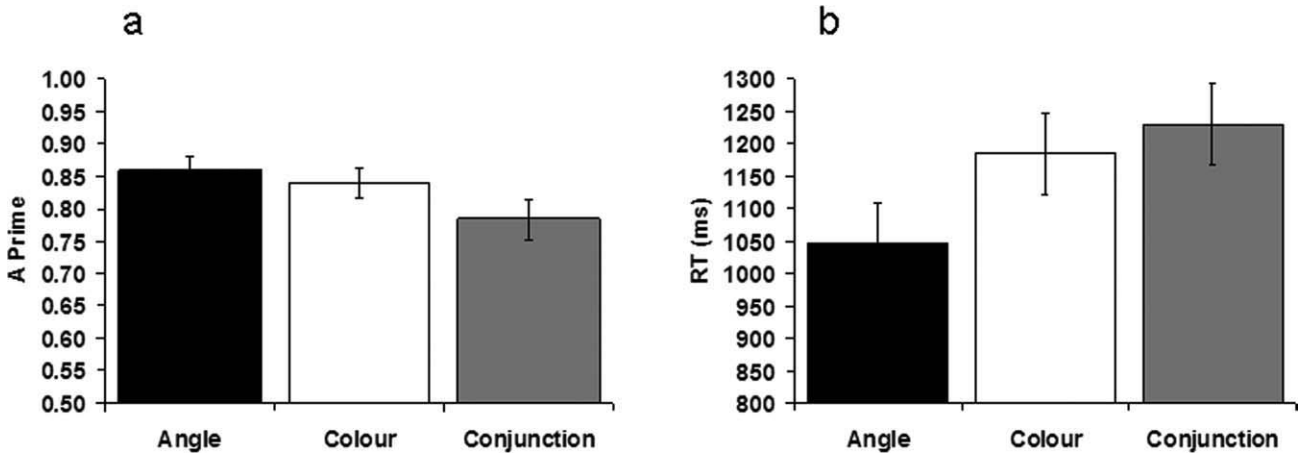

Figure 2.
Behavioral results obtained during fMRI. (**a**) Accuracy data are presented as A' values where 1 represents 100% accuracy and 0.50 represents chance performance. (**b**) Reaction times are presented in milliseconds (ms) in each condition. Bars represent ±1 standard error.

To gain insight into the time course of activity, individual subject event-related averaging plots were computed in selected ROIs. These time course data were extracted and activity across seventeen 1-s time points (to include the hemodynamic delay) was analyzed using paired samples *t*-tests to assess differences between task activity levels at particular time points.

In addition, we applied structural equation modeling (SEM) using the fMRI time series values to model effective connectivity among covarying brain areas that we found to be involved in the conjunction-task condition. Significant activation clusters were identified by our conjunction analysis described earlier. One time series per subject, comprising 17 s (starting from trial onset until the haemodynamic delay function returned to baseline), was extracted from each region-of-interest. SEM was conducted using AMOS version 16.0.1 [Arbuckle, 2007].

RESULTS

Behavioral Results

Figure 2 displays the behavioral results from the color, angle, and conjunction task conditions. Overall there was a significant main effect of condition on accuracy, $F_{2,34} = 8.62$, $P = 0.001$. While performance was equivalent for color ($A' = 0.85$, SE = 0.02) and angle ($A' = 0.86$, SE = 0.02) single tasks, $t_{17} < 0.5$, conjunction-task performance ($A' = 0.78$, SE = 0.03) was significantly worse than both color ($t_{17} = 3.80$, $P = 0.001$) and angle ($t_{17} = 3.10$, $P = 0.006$) single tasks. Thus, manipulating a combination of object and spatial information in WM resulted in a conjunction-task cost (discussed in more detail in the discussion). We also examined reaction time (RT) data on correct response trials only to determine whether any speed/accuracy trade-offs were present. We found a significant main effect of task, $F_{2,34} = 11.91$, $P < 0.001$, that reflected significantly faster RTs on angle (M = 1076.46 ms; SE = 61.55 ms) versus color (M = 1185.09 ms; SE = 62.94 ms) trials ($P = 0.02$) and angle versus conjunction (M = 1230.25; SE = 62.62) trials ($P = 0.001$). Coupled with our findings that accuracy was equivalent in angle and color conditions, and worse in conjunction than angle conditions, we conclude that no speed/accuracy trade-offs occurred.

Functional Imaging Results

As predicted from previous work, color-preferred activity was observed in left inferior frontal gyrus (IFG: $x = -40$, $y = 34$, $z = 18$) and right occipital cortex ($x = 18$, $y = -92$, $z = 0$) (Figs. 3a and 4a). Both these regions have been shown previously to be involved in the maintenance and manipulation of color versus angle [Mohr et al., 2006]. Angle-preferred activity was found in the right parietal cortex ($x = 19$, $y = -58$, $z = 53$), bilateral superior frontal sulcus (SFS: left $x = -19$, $y = -11$, $z = 51$; right $x = 26$, $y = -5$, $z = 55$), and left temporal cortex ($x = -46$, $y = -60$, $z = 8$) (Figs. 3a and 4b). Our finding of angle-preferred activation in right parietal cortex and bilateral SFS maps nicely onto previous work [Mohr et al., 2006; Sala and Courtney, 2007], as does activation in left temporal cortex [Munk et al., 2002]. To confirm this quantitatively, we computed a direct comparison of these Talairach-defined ROIs in our study with those in the studies cited earlier, using the formula to test for Euclidean distance in 3D space: square root $[(p_1 - q_1)^2 + (p_2 - q_2)^2 + (p_3 - q_3)^2]$, where p = our study, q = other study, $p/q_1 = x$-coordinate, $p/q_2 = y$-coordinate, and $p/q_3 = z$-coordinate. The closer the resulting number is to zero, the closer the regions are in Talairach space. There was a good fit between our and Sala and Courtney's regions: IFG = 14; rSFS = 3; lSFS

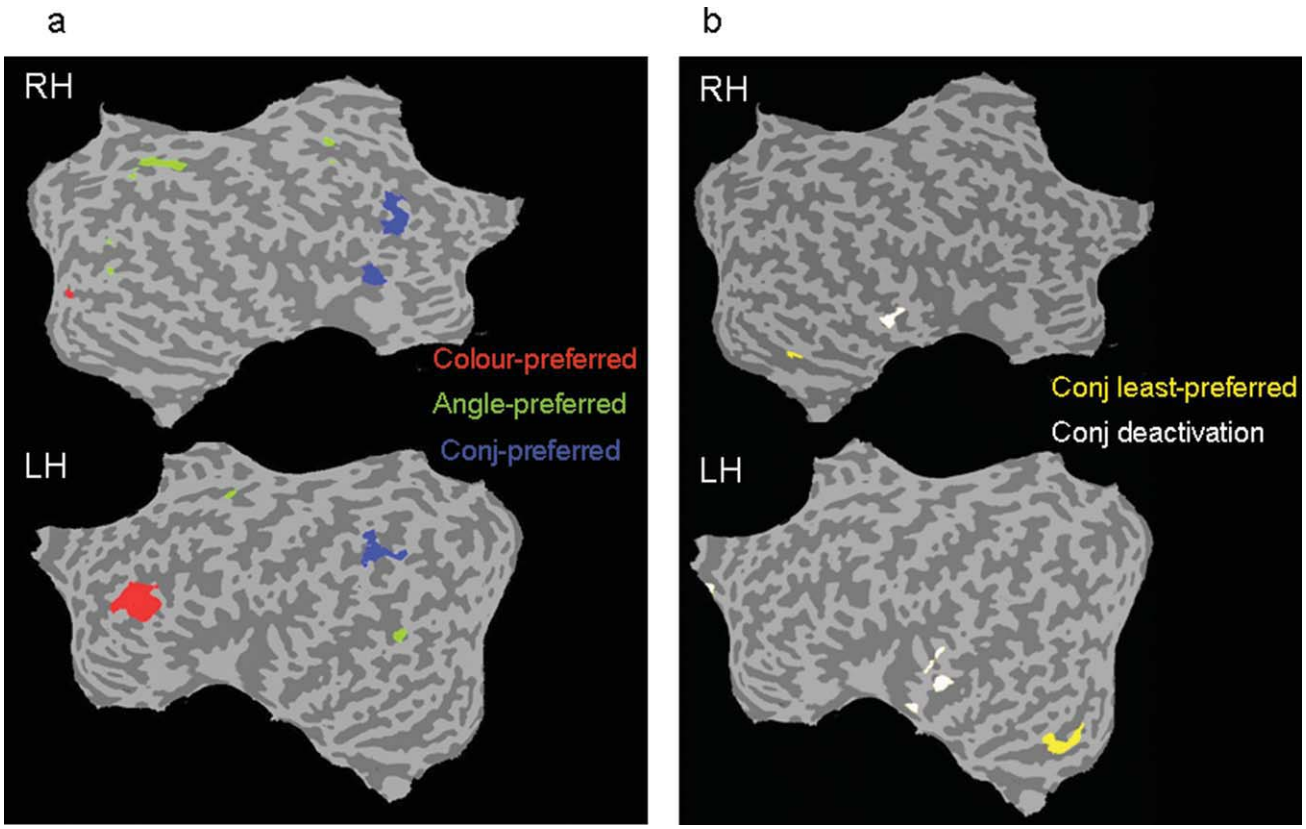

Figure 3.

Flatmaps of the right and left hemispheres show: (**a**) color-preferred regions in which activity was significantly greater on color than angle trials (red); angle-preferred regions in which activity was significantly greater on angle than color trials (green); conjunction-preferred regions in which activity was significantly greater on dual than both color and angle trials (blue); and (**b**) conjunction-least-preferred regions in which activity was significantly lower on dual than both color and angle trials (yellow); conjunction-deactivation regions in which activity was significantly more deactivated on dual than both colour and angle trials (white).

= 5; rParietal = 11, between our and Mohr et al.'s regions: IFG = 5; rSFS = 2; lSFS = 12; rParietal = 24, and between our and Munk et al.'s left temporal region = 5. These results approach consistency levels obtained for higher visual areas across different runs from the same participants (2–5 mm; [Peelen and Downing, 2005]), indicating a very good consistency between our and previous studies. The pattern of activity for color in an inferior portion of the frontal cortex and for angle in superior frontal cortical regions supports the domain-specific account of WM organization which postulates a ventral/dorsal separation for object and spatial tasks, respectively [Linden, 2007].

To examine conjunction-task trials, we first consider activity patterns in color- and angle-preferred regions. Next we report areas that showed highest ("conjunction-preferred") and lowest ("conjunction-least-preferred") conjunction-task activity compared to either single task. Finally, we present regions of deactivation for all conditions with enhanced deactivation for conjunction- versus single-tasks ("conjunction-deactivation"). We also assess whether task difficulty could account for our conjunction-task findings, presented in the final results section.

All patterns of activation are illustrated in Figure 3. Figure 3a shows color-preferred (red), angle-preferred (green), and conjunction-preferred (blue) regions; Figure 3b shows conjunction-least-preferred (yellow) and conjunction-deactivation (white) regions. Note that none of these areas overlapped anatomically, suggesting distinct neural processes in each task.

Conjunction task activity in color- or angle-preferred regions

All content-preferred areas (those with significantly greater activity for color versus angle or vice versa) showed a conjunction-task activation level that was intermediate between the preferred and nonpreferred single tasks. In left IFG, color was significantly greater than angle and conjunction ($P < 0.01$ in both cases) and conjunction was significantly greater than angle ($P < 0.01$). In right

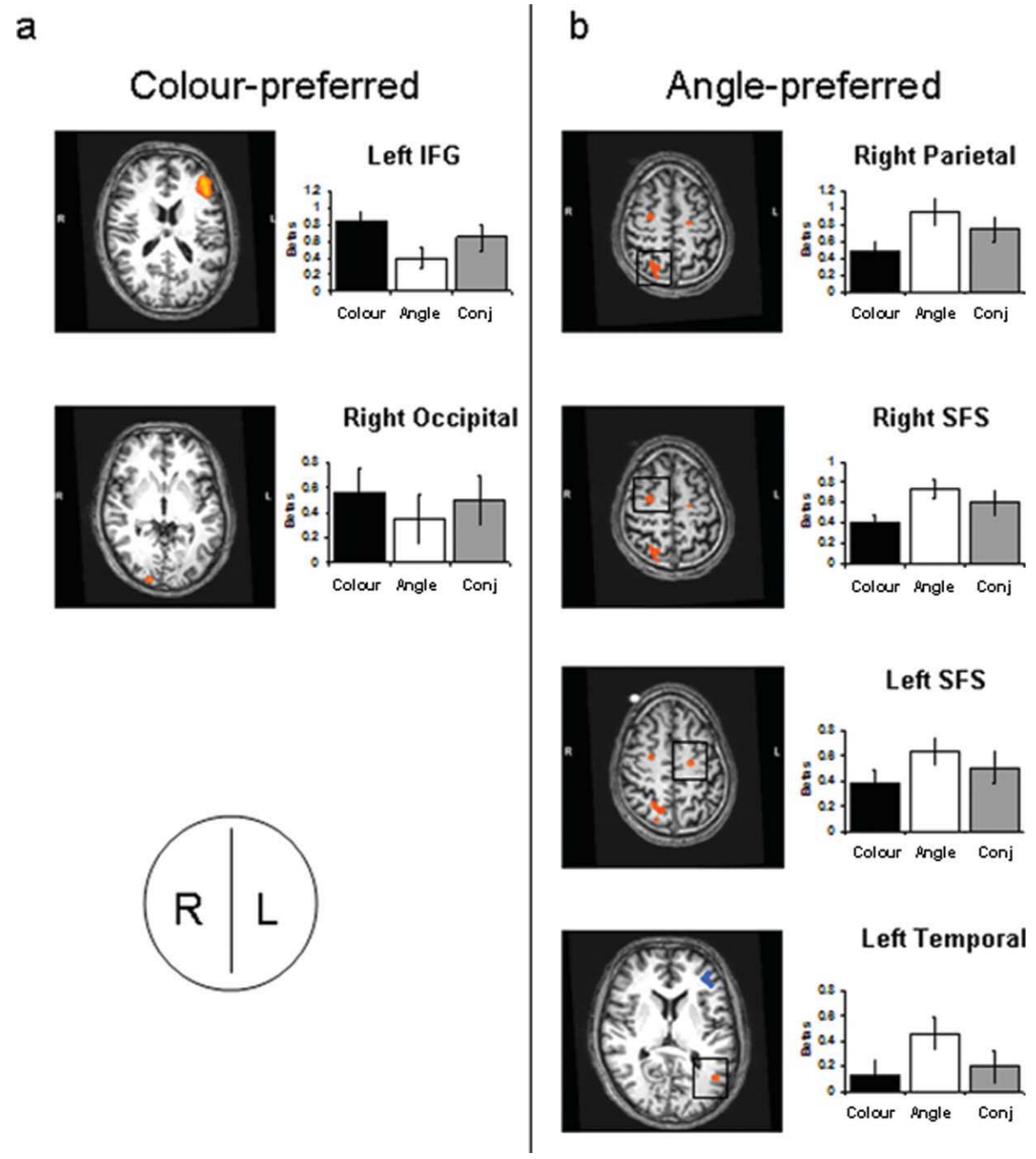

Figure 4.

Plots of beta values are presented to illustrate activation patterns during color, angle, and conjunction trials in (**a**) color-preferred regions and (**b**) angle-preferred regions. Bars represent ±1 standard error.

occipital cortex, color and conjunction were significantly greater than angle ($P < 0.01$ in both cases); the difference between color and conjunction was not significant ($P = 0.48$). See Figure 4a. In right parietal cortex, angle was significantly greater than color and conjunction ($P < 0.01$ in both cases) and conjunction was significantly greater than color ($P < 0.01$). In left SFS, angle was significantly greater than color and conjunction ($P < 0.01$ in both cases) and conjunction was significantly greater than colour ($P < 0.05$). In right SFS, angle was significantly greater than

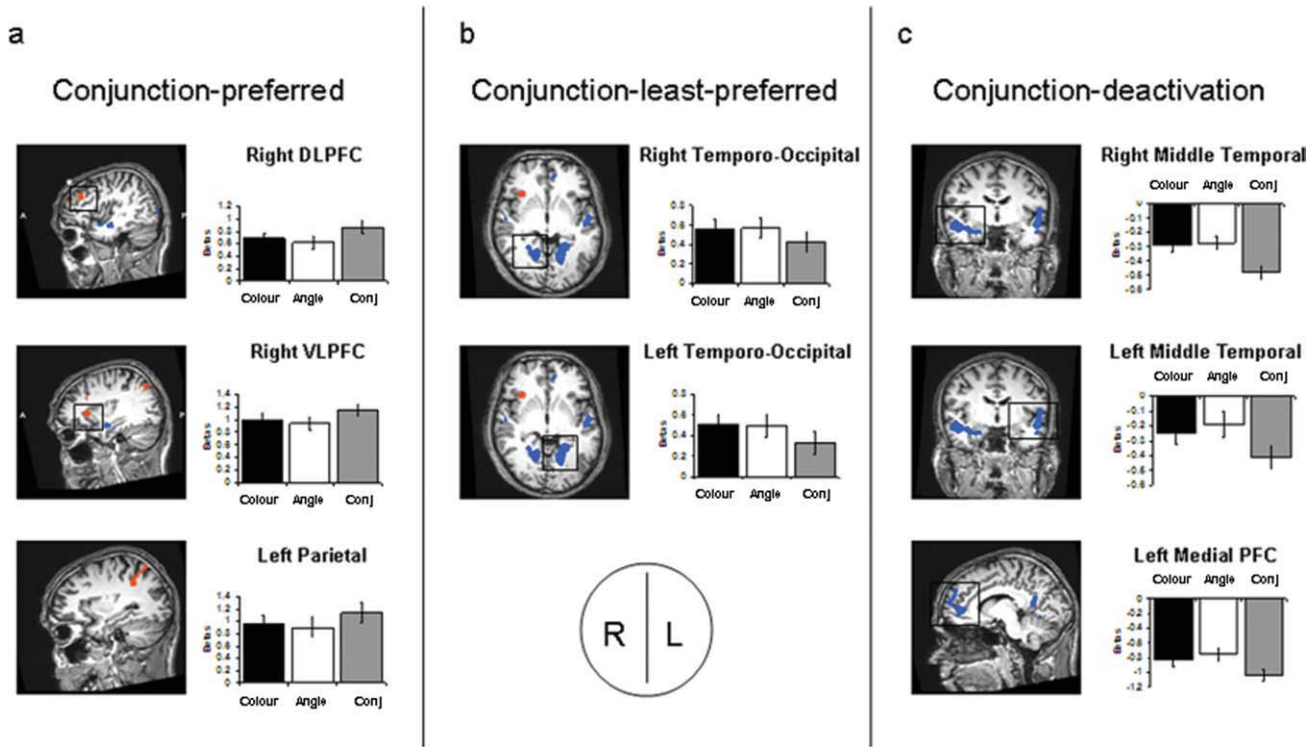

Figure 5.

Plots of beta values are presented to illustrate activation patterns during color, angle, and conjunction trials in (**a**) conjunction-preferred regions, (**b**) conjunction-least-preferred regions, and (**c**) conjunction-deactivation regions. Bars represent ± 1 standard error.

color ($P < 0.001$) and conjunction ($P < 0.05$), and conjunction was significantly greater than colour ($P < 0.05$). In left temporal cortex, angle was significantly greater than color and conjunction ($P < 0.001$ in both cases); the difference between color and conjunction was not significant ($P = 0.67$) (Fig. 4b).

Conjunction-preferred regions

Conjunction-preferred regions are defined as those in which conjunction-task activity was greater than both color and angle single-task activity. Three regions showed this pattern of activity: right dorsolateral PFC (rDLPFC: $x = 42$, $y = 31$, $z = 30$); right ventrolateral PFC (rVLPFC: $x = 34$, $y = 24$, $z = 4$); left parietal cortex ($x = -34$, $y = -51$, $z = 47$). In rDLPFC, conjunction was significantly higher than color and angle ($P < 0.01$ in both cases); in rVLPFC, conjunction was significantly higher than color ($P < 0.001$) and angle ($P = 0.02$); in left parietal cortex, conjunction was significantly higher than color ($P = 0.01$) and angle ($P < 0.01$). The difference between color and angle was nonsignificant in all three regions ($P = 1.0$ in all cases) (Fig. 5a). Previous studies showing conjunction-preferred activation also observed this pattern in regions of the frontal cortex. Using object identification (fruit images) and spatial location tasks, Munk et al. [2002] found higher conjunction-task activity in the medial superior frontal cortex bilaterally. Using verbal and spatial location tasks, Prabhakaran et al. [2000] found higher conjunction-task activity in the right PFC. Greater conjunction versus object single-task activity has been reported in the left superior parietal lobule [Munk et al., 2002], but our results provide the first evidence of increased conjunction versus spatial single-task WM activity in the parietal cortex. (Note that this pattern of activity was found in the left parietal cortex, a region that is distinct from angle-preferred activity in the right parietal cortex.)

Conjunction-least-preferred regions

Conjunction-least-preferred regions are defined as those in which conjunction-task activity was suppressed in relation to color and angle single-task activity. Here this pattern was observed in the temporo-occipital cortex bilaterally, extending to the lingual and parahippocampal gyri (left: $x = -18$, $y = -52$, $z = 2$; right: $x = 19$, $y = -50$, $z = -2$). In left temporo-occipital cortex, conjunction was significantly lower than color ($P < 0.001$) and angle ($P = 0.01$); in right temporo-occipital cortex, conjunction was significantly lower than color ($P < 0.01$) and angle ($P < 0.05$). In both regions, the difference between color and angle was

nonsignificant ($P = 1.0$ in both cases) (Fig. 5b). This is the first reported evidence of suppressed conjunction-task compared to single-task activity in WM studies designed specifically to address conjunction-task costs.

Conjunction-deactivation regions

Deactivation describes regions in which the level of brain activity is below baseline; baseline levels are determined during intertrial fixation periods during which no WM processes are active. Three regions showed deactivation wherein the conjunction-task condition elicited greater deactivation than the color or angle single-task conditions: bilateral middle temporal cortex, extending to the hippocampus in the right hemisphere (left: $x = -52$, $y = -11$, $z = 2$; right: $x = 42$, $y = -4$, $z = -13$) and left medial PFC ($x = -7$, $y = 54$, $z = 14$). In both left and right temporal cortices, conjunction deactivation was significantly greater than color and angle ($P = 0.001$ in all cases); the difference between color and angle was nonsignificant ($P = 1.0$ in both cases). In medial PFC, conjunction deactivation was significantly greater than color and angle ($P < 0.01$ in both cases); the difference between color and angle was nonsignificant ($P = 0.76$) (Fig. 5c). Not only is this the first reported evidence of deactivation during a manipulation WM task but also of greater deactivation for conjunction- versus single-tasks in WM.

Time course of activity in conjunction-preferred and least-preferred regions

Because of the novelty of finding greater conjunction- vs. single-task activity in right dorsal and ventral PFC and left parietal cortex, and conjunction suppression in bilateral temporo-occipital cortex, we examined the time course of this data in more detail to determine whether any early versus late contrasts could be drawn between these activation patterns.

Figure 6 shows the timecourses of activity among color, angle, and conjunction conditions in rDLPFC (6a), rVLPFC (6b), left parietal (6c), and left temporo-occipital (6d) regions (right temporo-occipital cortex activity was similar to that in the corresponding left hemisphere region so is not included). Each TR was 1 s in duration; TR of zero indicates the onset of the encoding display (encoding = 500 ms, followed by 2000 ms delay interval then 3000 ms probe/retrieval period). Peak differences between conjunction and single tasks were defined as the time point with the largest t-value obtained from the conjunction minus color and conjunction minus angle contrast, and are indicated by a dotted rectangle in Figure 6a–d.

Conjunction-preferred activity in rDLPFC (Fig. 6a) is elicited early at 3–4 s after the encoding display onset (conjunction vs. color, 4 s: $t_{17} = 3.38$, $P < 0.01$; conjunction vs. angle, 3 s: $t_{17} = 3.65$, $P < 0.01$), peaks at these time points, and is sustained until 10–12 s. Conjunction-preferred activity in rVLPFC (Fig. 6b) is similarly elicited early at 3 s after encoding onset (conjunction vs. colour, 3 s: $t_{17} = 2.28$, $P < 0.05$; conjunction vs. angle, 3 s: $t_{17} = 2.22$, $P < 0.05$). Unlike rDLPFC activity, conjunction-preferred activity in rVLPFC is short-lived and is not sustained beyond the early peak. Conjunction-preferred activity in left parietal cortex (Fig. 6c) has a similar onset to that in PFC regions but peaks later at 7–8 s (conjunction vs. color, 8 s: $t_{17} = 4.07$, $P < 0.01$; conjunction vs. angle, 7 s: $t_{17} = 3.07$, $P < 0.01$). Lower conjunction than single-task activity in left temporo-occipital cortex (Fig. 6d) is elicited and peaks at 8 s after encoding onset (conjunction vs. color, 8 s: $t_{17} = 3.41$, $P < 0.01$; conjunction vs. angle, 8 s: $t_{17} = 2.95$, $P < 0.0$), 4–6 s later than enhanced conjunction activity elicited in prefrontal and parietal regions.

Structural equation modeling

We applied structural equation modeling (SEM) to examine in more detail the functional relationship between conjunction-preferred (rDLPFC, rVLPFC, left parietal) and conjunction-least-preferred (temporo-occipital) regions. SEM is a multivariate analytical tool that is used to test hypotheses about directional influences among brain regions, and it has been used to determine functional and effective connectivity in a variety of WM studies [Schlösser et al., 2006]. Note that, in general, structural equation models do not incorporate temporal information. Although directionality is implied, SEM cannot determine for example the time point at which one pathway is active in relation to another.

We chose a path model, guided by our conjunction analysis, to determine connectivity patterns between our four conjunction-task areas of interest to better understand what happens in the brain during integration of manipulated object and spatial information. We used subject-averaged time course data to calculate standardized path coefficients using the maximum likelihood method. A path coefficient is expressed in terms of neural pathways and is defined as the "direct proportional functional influence one region has on another region through their direct anatomical connection, with all other regions in the model left unchanged" [McIntosh and Gonzalez-Lima, 1994, p. 10]. There are various fit indices for structural equation models: here we report chi-square (χ^2), goodness of fit (GFI), and comparative fit index (CFI) to give a rounded view of model fit (see [Smith and McMillan, 2001] for a review of model fit indices).

We adopted a model development approach in which we sought to determine the best model fit by modifying pathways between the four areas of interest. All relevant and feasible pathway combinations were tested. What we consider to be our best-fit conjunction-task SEM model (Model A) comprises (1) a bidirectional pathway between DLPFC and VLPFC, based on Sala and Courtney's [2007] proposal that under conjunction-task conditions object and spatial information is transmitted between these two regions via intrinsic or learned connections; (2) a unidirectional pathway from both DLPFC and VLPFC to left parietal cortex, based on evidence for a frontoparietal WM manipulation network [Mohr et al., 2006]; (3) a unidirectional pathway

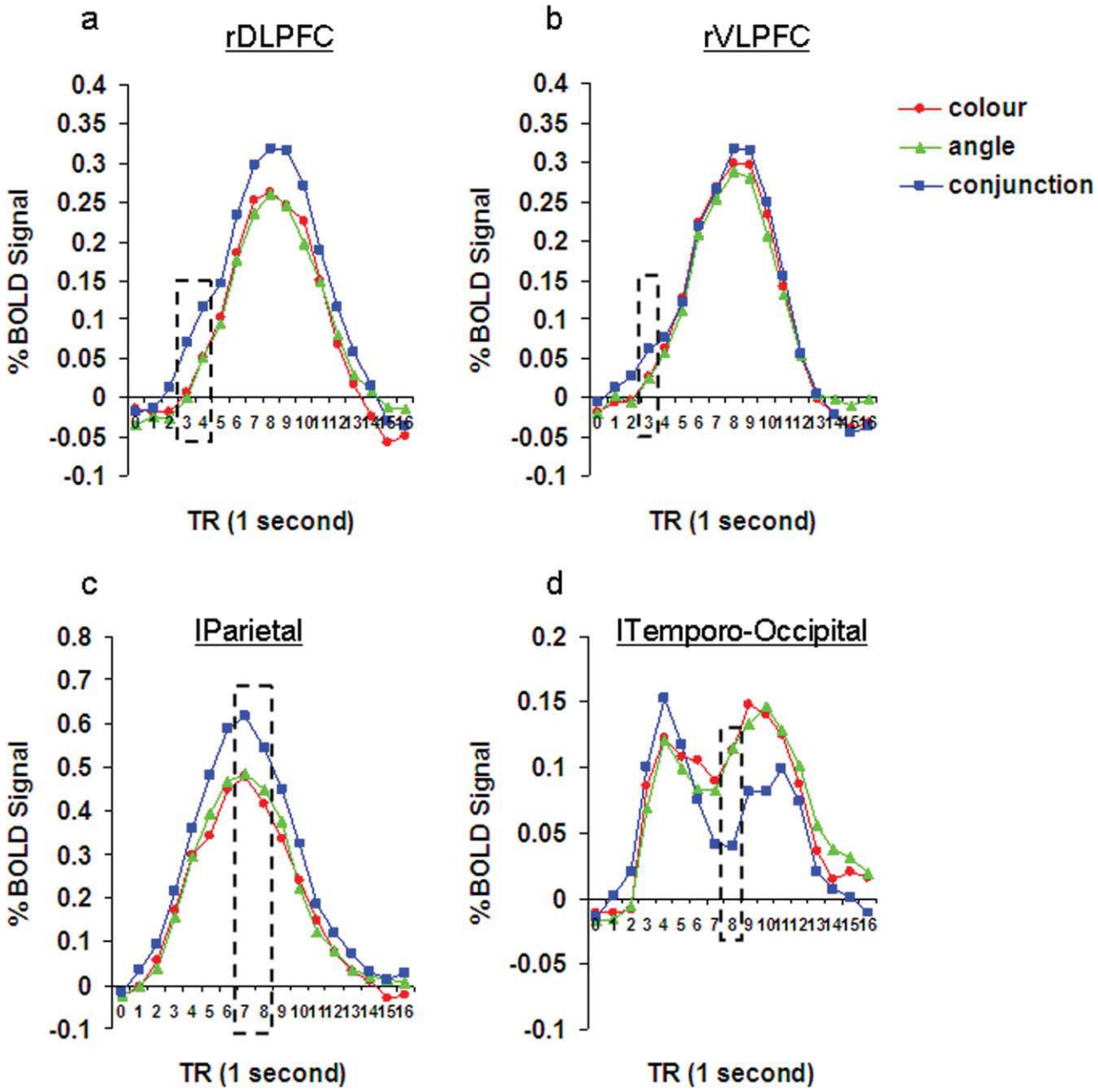

Figure 6.

BOLD activity levels for color, angle, and conjunction tasks at each time point (TR = 1 s) across a trial period are shown for the three conjunction-preferred regions (rDLPFC: **a**; rVLPFC: **b**; left parietal cortex: **c**) and one conjunction-least-preferred region (left temporo-occipital cortex: **d**). The peak differences in BOLD activity between conjunction versus colour and angle conditions (i.e., the largest *t*-values obtained in paired samples *t*-tests) for each region of interest is indicated by a dotted rectangle around the relevant data points.

from parietal to temporo-occipital cortex, reflecting top-down suppression of extrastriate areas via the parietal cortex. This connectivity model is shown in Figure 7A along with the fit indices. The numbers reported in Figure 7 are the path coefficients between each region. Path coefficients in structural equation models are not correlation coefficients; rather, they indicate the relative increase (positive coefficient) or decrease (negative coefficient) of activity in one region based on an increase in another connecting region. Coefficient values are expressed in terms of standard deviations from the mean.

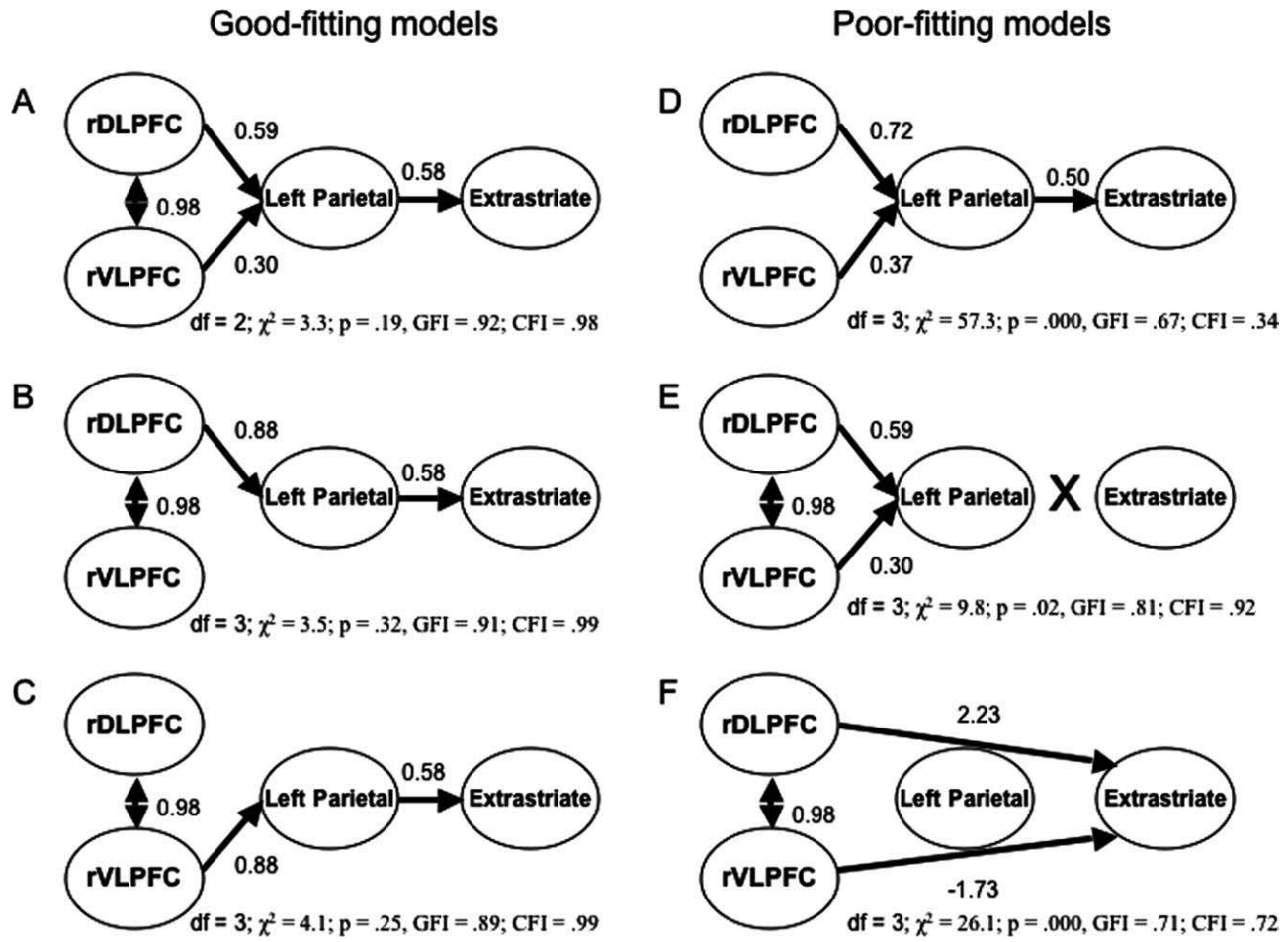

Figure 7.

We present three good-fitting and three poor-fitting conjunction-task functional connectivity models. The models were derived from our conjunction-color and conjunction-angle analysis that revealed greater conjunction- than single-task activity in rDLPFC, rVLPFC, and left parietal cortex, and lower conjunction- than single-task activity in temporo-occipital cortex. (A–C) Good-fitting dual-task Models A, B, and C involve a network of frontal, parietal, and extrastriate regions. There is a bidirectional pathway between rDLPFC and rVLPFC, across which it is proposed that spatial and object information is shared to facilitate visuospatial integration; the frontoparietal pathway involves the connection of dorsal and/or ventral PFC with the left parietal cortex; parietal and temporo-occipital cortices are connected, indicating the importance of extrastriate suppression in the coordination of conjunction-task processes. (D–F) Poor-fitting dual-task models D, E, and F illustrate the importance of a frontoparietal network and a parietal-extrastriate connection.

For example, if there is a pathway from region A to region B with a coefficient of 0.60, this means that if activity in region A increases by one standard deviation from its mean, activity in region B is expected to increase by 0.60 of a standard deviation from its own mean, while holding all other relevant regional connections constant. If the coefficient were −0.60 then activity in region B would be expected to *decrease* by 0.60 of a standard deviation [Chen et al., 2007]. Note that positive and negative path coefficients are not evidence of excitatory and inhibitory influences [Schlösser et al., 2006].

The path coefficients in Model A were as follows: 0.98 between DLPFC and VLPFC; 0.59 between DLPFC and parietal; 0.30 between VLPFC and parietal; 0.58 between parietal and temporo-occipital cortex.

We tested two alternative models in which there was a bidirectional pathway between DLPFC and VLPFC but a unidirectional pathway from either the DLPFC to parietal cortex (Model B, Fig. 7B) or VLPFC to parietal cortex (Model C, Fig. 7C) to determine whether a good connection between DLPFC or VLPFC and parietal cortex could exist without direct input to the parietal cortex from VLPFC or DLPFC, respectively. If information is shared across these frontal regions, perhaps both dorsal and ventral PFC comprise similar information and therefore only

one of these regions is required to feed information effectively to the parietal area. This is in fact what the models confirmed. Model B illustrates a good-fitting model, indicating that a parietal connection to only DLPFC is sufficient for an effective conjunction-task model. Similarly, Model C is a good fit, suggesting that a parietal connection to only the VLPFC is sufficient for conjunction-task coordination. Path coefficients for Models B and C were 0.98 between DLPFC and VLPFC; 0.58 between parietal and temporo-occipital cortex; 0.88 between DLPFC/VLPFC and parietal.

We also tested a model in which there was no connectivity between DLPFC and VLPFC (Model D), and a model that excluded temporo-occipital cortex (Model E). Model D illustrates a very poor fit model when no bidirectional pathway exists between DLPFC and VLPFC; Model E is overall a poor fit model that demonstrates the importance of including suppression of extrastriate areas in the conjunction-task connectivity model. Finally, we tested a model that excluded the parietal cortex, comprising a direct connection from both DLPFC and VLPFC to temporo-occipital cortex (Model F). Model F illustrates a very poor-fitting conjunction-task model in the absence of a frontoparietal network.

Task difficulty effects

It is important to establish that the conjunction-related activation patterns seen here are due to integration and coordination processes rather than task difficulty effects. To do this we split participants into two groups according to whether they showed a high or low conjunction-task cost. Conjunction-task cost was calculated by subtracting the conjunction Aprime scores from the average of both single task scores; high/low groups were identified by computing the median conjunction-task cost value and forming a median split between participants, yielding nine participants in each group. Our rationale is that the high-cost group found the conjunction task proportionately more difficult to the single tasks than the low-cost group. Confirming this, we found that WM performance did not significantly differ between high and low cost/difficulty groups in either the color ($P = 0.62$) or angle ($P = 0.79$) single tasks, evidence that the conjunction- versus single-task costs were calculated using equivalent single-task baselines in each group. In the conjunction condition, WM performance was significantly worse in the high- versus low-cost group ($P < 0.01$), as expected.

We compared brain activity data in each conjunction-specific region between high- and low-cost participants. We hypothesized that if difficulty specifically modulated conjunction-task activity (and not single-task activity) in these areas then we would see a high versus low group difference in brain activity (either increased or decreased) in the conjunction-task condition but not in the single-task conditions, evidenced by a group by task interaction. None of the conjunction-preferred, conjunction-least-preferred, or conjunction-deactivation regions showed an interaction of group by task (all P's > 0.50), suggesting that task difficulty is unlikely to account for the patterns of conjunction-related activity found here.

We did find a marginally significant main effect of group in the left medial PFC ($P = 0.08$) wherein the high-cost group showed less deactivation than the low-cost group across all three task conditions. Deactivation in this region is commonly reported as part of the "default network," a collection of brain areas that are active when a person is unfocused on a task and show deactivation when the brain is engaged with internalized mental tasks such as memory retrieval [Buckner et al., 2008; Buckner and Vincent, 2007]. This effect suggests that the default mode network might be influenced by some aspect of the high conjunction-task cost group, but the fact that both single- and conjunction-task conditions show this pattern makes it hard to conclude that task difficulty accounts for this result.

To further test whether task difficulty could account for our findings, we computed a between-group (high- vs. low conjunction-task cost) contrast in the conjunction-task condition only to reveal brain areas sensitive to task difficulty and to ascertain whether any of these difficulty-related areas overlapped with conjunction-preferred, -least-preferred, and -deactivation areas. The high- versus low-cost group revealed several areas in bilateral PFC and left parietal cortex that were more active in the high- than low-cost group at FDR < 0.05. The frontoparietal network has been implicated in top-down control of attention [Hopfinger et al., 2000], and activity in the PFC has been shown to scale with attentional demands [Mayer,et al., 2007], suggesting that our finding of activity differences between groups in these regions does indeed reflect differences in effort and/or task difficulty. Importantly, these regions did not anatomically overlap with any of the conjunction-preferred, -least-preferred, or -deactivation regions, apart from a small portion of the left medial PFC that does not appear to be difficulty-related, as discussed earlier (see Supporting Information Fig. S4). No regions showed lower activity for the low- versus high-cost group. The finding that these difficulty-related regions in the prefrontal and parietal cortices were anatomically distinct from the conjunction-related task-specific regions is important because it suggests that although task difficulty might have been a factor in the lower conjunction- versus single-task behavioral performance, our interpretation of the conjunction-specific areas of brain activation as being unrelated to task difficulty remains intact. We conclude that in this study task difficulty is unlikely to account for our findings.

DISCUSSION

We found a small conjunction-task performance deficit when participants were required to manipulate in WM both color (object) and angle (spatial) properties from the

same object (conjunction-task) compared to manipulation of only color or angle (single-tasks). We found color-preferred regions in left IFG and right occipital cortex and angle-preferred regions in the right parietal cortex, bilateral SFS, and left temporal cortex. The conjunction-task condition elicited activation in these same regions but to an intermediate degree between preferred and nonpreferred single-task activity. Conjunction-preferred regions were identified in right dorsolateral and ventrolateral PFC, and left parietal cortex. Conversely, bilateral temporo-occipital activity was suppressed for conjunction versus both single tasks (conjunction-least-preferred), the first evidence of this pattern of activity during a WM conjunction task. Conjunction-preferred activity peaked early in right dorsal and ventral PFC (reflecting encoding). The conjunction-preferred activity in left parietal cortex peaked later, corresponding with lower conjunction activity in bilateral temporo-occipital cortex. Also of novel interest, areas of deactivation were identified in bilateral middle temporal cortex and left medial PFC wherein conjunction-task activity was lower than that elicited by either single task.

Conjunction-Task Performance Cost

The presence of a conjunction-task cost during a conjunction object and spatial WM task is not what would be predicted from traditional theories of WM organization wherein it is proposed that two concurrent and different WM processes do not interfere with each other [Baddeley and Hitch, 1974]. Nor does it fit with previous results using a similar paradigm (conjunction-task performance was equivalent to the harder of the single tasks; [Mohr and Linden, 2005]). There are two factors that might account for our findings. First, we took care to pilot our experiment to achieve equivalent performance levels for both color and angle single tasks and thus equate task difficulty. Mohr and Linden found that performance was worse on spatial than object single tasks and conjunction-task performance was equivalent to spatial task performance, therefore making it difficult to select a definitive interpretation of whether a conjunction-task cost did exist (conjunction vs. color) or not (conjunction vs. angle). In addition, the tasks used in Mohr and Linden's study were slightly different to the current design: we presented the instruction cue before the sample display whereas in their most similar experiment (Experiment 1) they presented the cue just after the sample display. Perhaps differential preparation strategies could account for the discrepant findings between studies. Second, most previous tasks that elicited equivalent performance across all single and conjunction object and spatial tasks required maintenance in WM [Sala and Courtney, 2007], whereas we investigated manipulation. It has been shown that manipulation in WM elicits higher activity in frontoparietal regions than maintenance, reflective perhaps of greater recruitment of executive processes that enable more top-down control of WM [Mohr et al., 2006]. If demand on executive processes is greater during WM manipulation than maintenance (and single tasks are equated for task difficulty), perhaps insufficient executive resources remain for manipulating object and spatial information concurrently in WM to achieve a level of performance equivalent to the single tasks.

Our finding of a small conjunction-task cost suggests that manipulating a combination of object and spatial information in WM might not proceed in an entirely parallel fashion. However, the fact that conjunction-task performance is only 8–9% lower than that observed in either single task suggests that some degree of successful integration of separable object and spatial processes has been achieved.

We also found slower RTs in the conjunction than angle task, which could suggest that more effort was required to compute the conjunction manipulation. However, there was no difference in RTs between the conjunction and color task even though accuracy was significantly poorer in the former, and significantly faster RTs in the angle than color task even though accuracy was equivalent. While slower RTs might reflect less task effort, the lack of systematic direction of RTs and accuracy effects makes it hard to make any clear judgment on whether RT differences reflect a scaling of task difficulty. The lack of RT difference between conjunction and color tasks might suggest that participants focused on color more than angle information to perform the conjunction task, but this is an unlikely strategy if the color task requires more effort, as perhaps suggested by slower RTs in the color than angle single tasks.

Intermediate Conjunction-Task Activity in Domain-Preferred Regions

Our finding that the amplitude of BOLD signal change during conjunction-task trials in color- and angle-preferred brain regions was intermediate to levels of single-task activity is consistent with previous studies of WM maintenance of object and spatial information [Munk et al., 2002; Sala and Courtney, 2007]. Thus, manipulating both color and angle properties concurrently in WM does not result in a simple linear addition of the neural demands of each single task. Sala and Courtney proposed that the model of biased competition [Desimone, 1996; Desimone and Duncan, 1995] could account for this pattern of activity in WM. In this model, excitatory biasing signals, thought to be transmitted both to and from the PFC along dorsal and ventral pathways enhance the representation of task-relevant information in domain-specific regions. As a result, color information is processed preferentially over spatial information in the color task, and vice versa. To achieve this, object and spatial representations mutually inhibit one another, such that activity in the spatial-dorsal pathway is inhibited when only object information is task-relevant, and activity in the object-ventral pathway is inhibited when only spatial information is task-relevant.

During single tasks this results in higher activity in color- or angle-preferred regions that receive the biasing signal. When both object and spatial information are task-relevant (i.e., during a conjunction-task trial), mutual inhibition results in lower activity in color- and angle-preferred regions during conjunction-task trials compared to single-task trials because there is no dominating bias to either task region. As such, the nature of object and spatial representations in domain-specific regions is altered according to task demands.

Sala and Courtney's [2007] biased competition account differs from domain-specific theory in that colour- and angle-preferred regions in the dorsal and ventral stream are proposed to contain a subset of cells that are sensitive both to object and spatial information, as opposed to only cells that are exclusively tuned to one or the other. In addition to receiving signals from object- and spatial-preferred regions that indicate task demands in a bottom-up fashion, the PFC mediates performance in a top-down manner by biasing activity in color, angle, or dual color/angle cells.

One question prompted by Sala and Courtney's [2007] model concerns whether mutual inhibition between object and spatial activity during a conjunction-task WM trial occurs in parallel or serial fashion. On one hand, the PFC might send or receive biasing signals along each dorsal and ventral pathway concurrently. On the other hand, biasing signals might be sent/received alternately along dorsal then ventral (or vice versa) routes in a task-switching manner. While Sala and Courtney found no behavioral conjunction-task performance cost, suggesting parallel processing, we did find such a cost which could be interpreted as evidence for serial processing of color and angle during the conjunction-task condition. We would argue, however, against an interpretation of our data that falls solely on serial processing, for three reasons. First, our conjunction-task cost does not present as a marked drop in conjunction versus single performance as would be expected by a fully serial processing account: conjunction performance accuracy is only 9.3% and 8.2% lower than color and angle accuracy, respectively. Second, serial processes might manifest in slower RTs for conjunction- versus both single-task trials, but we only find this pattern of results for conjunction compared to angle trials. Third, the fact that intermediate conjunction-task activity is observed across studies regardless of whether a conjunction-task cost in performance is present or not, suggests that this pattern of neural activity is not the key mechanism underpinning the conjunction-task cost observed in our study. An alternative interpretation of our small but significant conjunction-task cost is that of a limited-capacity parallel processing model, which might be indistinguishable from that of a fast serial processing account [Bundesen, 1990]. In the limited-capacity parallel model [Broadbent, 1982; Kahneman, 1973; Neisser, 1967; Treisman, 1964], manipulation of color and angle would be computed at the same time, but the quality of the resulting representation would be lower than that produced on single tasks when each parameter was manipulated individually. This account, rooted in theories of early attentional selection, supports the suggestion that attentional bottlenecks underpin conjunction-task costs [Pashler, 1994], and would fit with our finding of early conjunction-preferred activity in dorsal and ventral PFC.

It might also be possible that intermediate conjunction-task activity in color and angle-preferred regions is a result of reduced availability of blood supply ("blood stealing") due to greater activity during conjunction- versus single-task trials in different prefrontal and parietal regions, required for the coordination and integration of two tasks. However, because of the relatively low levels of BOLD signal change observed in this study (up to 0.62% at 3 Tesla) this is not a likely explanation.

Conjunction-Preferred Activity

Evidence for conjunction-preferred activity in right dorsolateral and ventrolateral PFC is in line with previous studies of conjunction in WM which report additional, higher activity in frontal regions during conjunction- versus single-task conditions [Mitchell et al., 2000; Munk et al., 2002; Prabhakaran et al., 2000]. The exact regions additionally active appear to differ between the current and previous studies, and this is likely due to differences between stimuli and tasks. Greater activation in the rDLPFC and rVLPFC might reflect higher demands on executive (e.g. attention) resources required to coordinate the manipulation of spatial and object information respectively during conjunction-task trials. In their biased competition model of WM, Sala and Courtney [2007] propose that the PFC, in addition to serving as the source, is also the target of biasing signals from domain-preferred object and spatial regions. They suggest that, under conjunction-task conditions, VLPFC receives object information and DLPFC receives spatial information in a feed-forward manner, and crucially that object and spatial task-relevant information is also transmitted across the PFC in a bidirectional manner to dorsal and ventral regions respectively via intrinsic or learned connections [Miller, 2000], thus enabling single cells in PFC to comprise conjunction object and spatial selectivity. Our SEM results provide valuable support for this account: the best-fit models of conjunction-task connectivity (Fig. 7A–C) required a bidirectional connection between DLPFC and VLPFC regions that were found to be more active during conjunction- than single-task trials.

Sala and Courtney [2007] proposed that during single-task trials, the flow of information across the PFC is unidirectional as only task-relevant information is transmitted from one region to the other. In this study, we find equivalent levels of color and angle activity in both rDLPFC and rVLPFC during single-tasks, a finding that supports this notion of information sharing across dorsal/ventral PFC. Greater activity in these PFC regions for conjunction

versus single tasks (in the magnitude of around 17–20%) might then reflect the convergence of the inputs from the dorsal and ventral streams because the added activity in both streams was higher for conjunction than either of the single conditions (Fig. 5a). The activity in the right PFC, which has been shown to scale with attentional demand during memory encoding [Mayer et al., 2007], may furthermore reflect the added need for resource allocation and organization of material in the conjunction condition. As mentioned earlier in regard to a capacity-limited parallel processing model, and as indicated by the rDLPFC and rVLPFC timecourses (Fig. 6), attentional resources may be deployed early to coordinate the two tasks.

We also present the first evidence of greater conjunction- versus single-task activity in the parietal cortex in a WM manipulation task. This difference in activity peaks about 4 s later than that found in prefrontal regions. Regions of the posterior parietal cortex have found to play a role in visuospatial attention and WM processes [Corbetta et al., 2002] and recently the superior parietal cortex has been shown to play a critical role in WM tasks involving manipulation specifically [Koenigs et al., 2009]. In addition, there is evidence that parietal regions are involved in binding object and spatial features. Shafritz et al. [2002] found greater activity in superior and intraparietal cortices when participants had to maintain both the color and the shape of two abstract polygons in WM versus color and shape alone. Our findings support the notion of the parietal cortex as a site of information integration [Marois and Ivanoff, 2005], and extend this role to include the integration of manipulated object and spatial representations in WM. Furthermore, we show that good fitting conjunction-task connectivity models (Fig. 7A–C) require a frontoparietal network that involves both or either of the dorsal and ventral PFC regions. Our conjunction-task WM model thus reflects a frontoparietal network that is not domain-specific to ventral or dorsal pathways. Lending authenticity to our finding, monkey research has identified several large fiber tracts that connect dorsal and ventral parietal regions to the PFC, with these tracts suggested to play an important role in attention and WM [Makris et al., 2005; Schmahmann et al., 2007; see Olson and Berryhill, 2009 for a discussion of frontoparietal connections].

The conclusions about frontoparietal networks drawn from our SEM analysis are limited by the distribution of conjunction-preferred areas across hemispheres. There are probably no monosynaptic connections between right PFC and left parietal lobe, and thus the functional connectivity between these regions is likely mediated through left prefrontal or right parietal regions that vary too much between individuals to be detected in the present group analysis.

Conjunction Least-Preferred Activity

Unique to our study, we found that activity in bilateral temporo-occipital cortex was lower during conjunction- versus single-task trials (conjunction-least-preferred regions) in our WM manipulation task. We can account for this pattern of activity by extending the biased competition model. One reason why the color/angle information elicits less brain activity at some stage of the processing of the conjunction task might be that irrelevant information needs to be discarded. Participants need to avoid following the color cues in the angle condition, or the angle cues in the colour condition. In the single conditions it sufficed to suppress the irrelevant dimension in dorsal and ventral regions, an effect we observed to be elicited relatively early on (around 4 s post-encoding onset) and sustained throughout the trial period. Conversely, in conjunction-task trials both object and spatial information is relevant during encoding, but at the retrieval stage neither of the single-task domains must evoke a prepotent response because this would lead to false positive responses. It is therefore conceivable that lower activity in the extrastriate/medial temporal complex during conjunction- compared to single-tasks reflects a small degree of inhibition of color/angle information in the probe stimulus to avoid such prepotent responses and allow for coordination between domains. It is likely that such a pattern would occur later in the WM process after dorsal/ventral competition has been initiated in the PFC, for example during maintenance or retrieval rather than at encoding. Our finding that the peak of conjunction- versus single-task in these regions showing lower conjunction than single task activity occurs relatively late at around 8 s post-encoding onset supports this notion of late inhibition in extrastriate cortex. In support of our proposed explanation, previous studies have reported top-down suppression of visual areas from prefrontal cortex during a remember/ignore WM task for faces and scenes [Gazzaley et al., 2005, 2007], and suppressed activity in visual cortex has been suggested to resolve competition among stimuli [Kastner and Ungerleider, 2001]. In addition to modulation of early visual areas, attentional modulation also has been shown to operate on extrastriate visual cortex [Corbetta et al., 1991; Kastner et al., 2001].

Our results suggest that during a conjunction task the PFC not only sends early excitatory biasing signals to domain-specific regions but may also be the source of later inhibitory signals to extrastriate cortex. During single-task trials, this downregulation of activity in extrastriate at around the time of retrieval is not required as inhibition of the irrelevant information has been achieved earlier in domain-specific regions. Our good-fit conjunction-task WM connectivity models (Fig. 7A–C) require modulation of the extrastriate area via the frontoparietal regions. This further highlights the importance of top-down inhibition of higher-level visual areas under conjunction-task WM conditions.

We acknowledge that our explanations of conjunction suppression are post-hoc, but we still regard them as valuable because they can generate hypotheses for further research into the more detailed mechanisms of memory retrieval.

Conjunction Deactivation

Another novel finding in this study was greater deactivation during the conjunction-task compared to both single tasks in bilateral middle temporal cortex and left medial PFC regions which are implicated in the default mode network. Such deactivation patterns, which have been shown to scale with task difficulty [McKiernan et al., 2003] and specifically with memory load [Mayer et al., 2010], might reflect inhibition of irrelevant non-task-related information to enable efficient resource allocation for conjunction-tasks under conditions of limited WM capacity.

An Extended Model of Biased Competition in WM

To incorporate all patterns of conjunction-related activity observed in the current study, we propose an extension of Sala and Courtney's [2007] biased competition model of WM (Fig. 8). Note that model components numbered 1, 2, and 3 in Figure 8 comprise components proposed in the original Sala and Courtney model, and those numbered 4 and 5 are new additions proposed here in line with our current findings.

During conjunction-task trials, object (color) information is fed forward along the ventral processing pathway, via temporo-occipital areas to VLPFC; spatial (angle) information is transmitted along the dorsal processing pathway, via parietal areas to dorsal premotor cortex. Competition between object and spatial processes is initiated as information travels along the ventral and dorsal pathways because both are task-relevant; excitatory biasing signals between the PFC and color/angle-preferred regions serve to enhance attention to both color and angle information, and the resultant mutual inhibition between the two processes elicits intermediate levels of activity in conjunction-task color- and angle-preferred regions compared to the single tasks.

Both dorsal and ventral streams converge onto coordination areas in DLFPC, VLPFC, via shared reciprocal connections between each frontal region, and also parietal cortex, resulting in highest activation during the conjunction condition. This initial stage of information integration appears to engage early at around 3–4 s post-encoding onset, and corresponds with the start of conjunction-preferred activity in left parietal cortex. Our structural equation Models A, B, and C (Fig. 7A–C) provide new support for the presence of reciprocal connections between DLPFC and VLPFC in two ways. First, we demonstrate that any conjunction-task model must include a bidirectional pathway between dorsal and ventral PFC. Second, with Models B and C we additionally show that an effective model of conjunction-task processing can comprise a frontoparietal network that includes a parietal connection to only dorsal (Model B) or ventral (Model C) prefrontal cortex. This latter finding supports prior suggestions that the prefrontal cortex is multifunctional in terms of object/spatial/maintenance/manipulation functions [Courtney, 2004; Mohr et al., 2006; Postle, 2006; Volle, 2008], suggests that information is shared between dorsal and ventral PFC regions, and implies that one region might be able to act without the support of another.

Conjunction-preferred activity in parietal cortex is sustained from its early onset and peaks at around 8 s, suggesting that perhaps the integration of color and angle manipulations is consolidated in this region. Biasing signals from PFC are transmitted back towards color- and angle-preferred regions, perhaps in a recursive online monitoring fashion, as manipulation of both dimensions in WM is underway. In support of this, examination of the time courses from angle- and color-preferred regions indicates that greater conjunction- than nonpreferred single-task activity is initiated early and sustained throughout the trial period. Our finding that later activity in extrastriate cortex is lower in conjunction than single tasks suggests that, once an integrated representation has been created, top-down inhibitory signals are transmitted from the DLPFC (in which conjunction-preferred activity is elicited early and sustained throughout the trial period), via the parietal cortex, back to temporo-occipital cortex. We propose that this serves to reduce interference that could potentially arise from the single-probe stimulus presented at retrieval, which could be mismatched (66% of trials) on either color or angle properties with the contents of WM. That is, greater conjunction suppression in extrastriate visual areas might serve to reduce retroactive interference from task-relevant color and angle probe information at retrieval.

It is worth considering the nature of the parietal-extrastriate pathway in our good-fitting SEM models (Fig. 7A–C) in more detail to understand this top-down inhibition. Our models show that an increase in activity of one standard deviation from its mean in parietal cortex is related to an increase of 0.58 standard deviations from the mean activity in extrastriate cortex. In other words, greater activity in parietal cortex is related to *less* suppression in extrastriate cortex. One might speculate from this connectivity pattern that if a visuospatial representation is robustly consolidated or integrated in WM, assumed to be related to higher parietal activity, there is less need to inhibit activity in extrastriate regions to reduce interference from the probe: a well-integrated representation will suffer less from interference in WM than a poorly-integrated one. Alternatively, increased parietal activity might reflect greater conjunction-task difficulty (increased effort), in which case reduced extrastriate inhibition might be due to lack of available resources (e.g., attentional) that are required to limit interference from the probe, thus increasing task difficulty. We compared parietal activity during conjunction task trials for high- versus low-conjunction task cost groups (as defined in the difficulty analysis above) and found a nonsignificant difference, $t(16) = 1.22$,

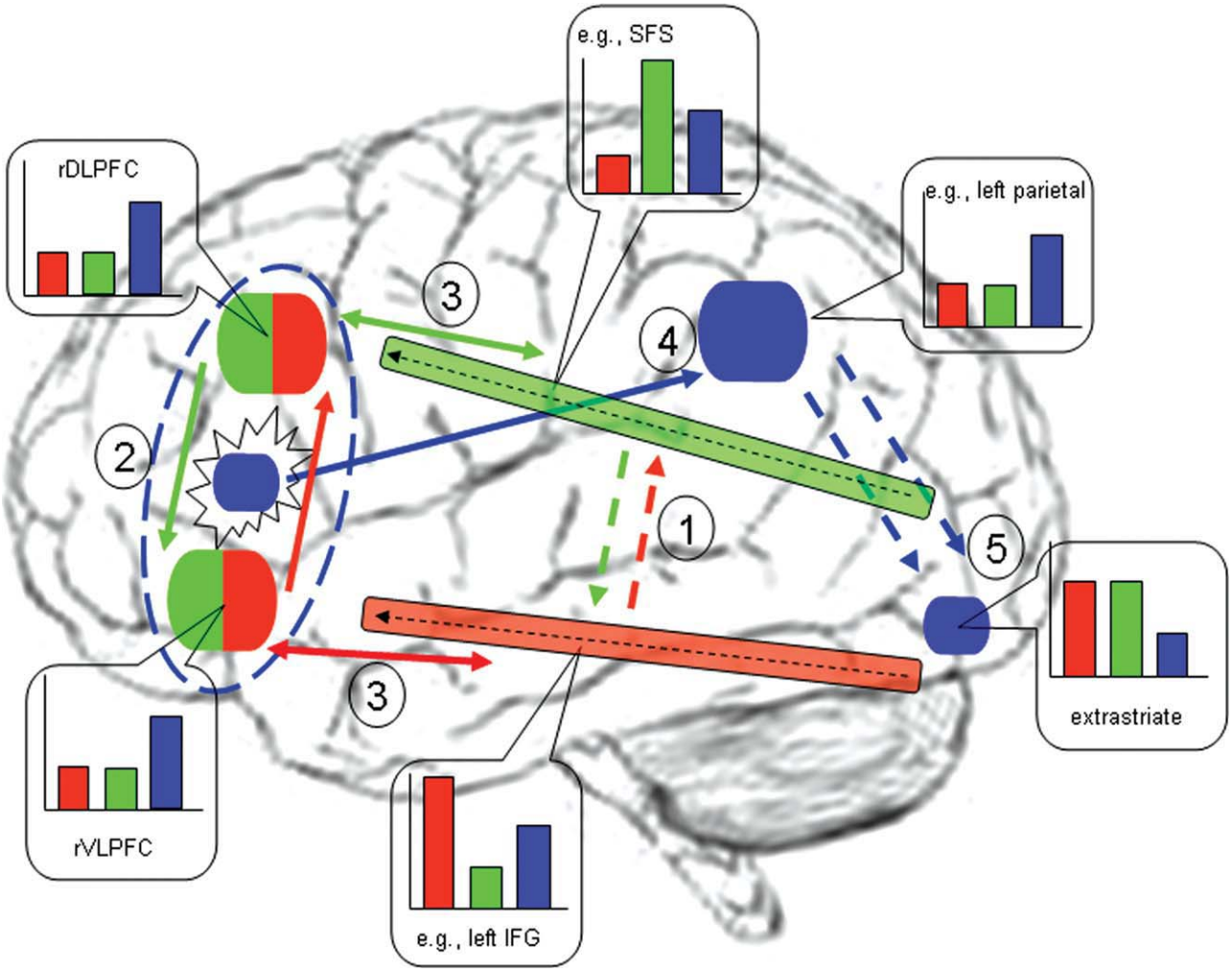

Figure 8.

Here we propose a new extended version of the biased competition model of WM [Sala and Courtney, 2007] during a conjunction-task trial. Red objects denote color activity, green objects denote angle activity, and blue objects denote coordinated conjunction activity. Blocked arrows indicate facilitatory connections; dashed arrows indicated inhibitory connections. The bar charts illustrate the pattern of BOLD activity in each condition. The numbers on the figure correspond to each of the following component processes. (1) Color and angle information travels along color-preferred ventral (i.e. right occipital cortex and left IFG) and angle-preferred dorsal (i.e., bilateral SFS, left temporal cortex, and right parietal cortex) pathways respectively. Mutual inhibition occurs between these regions as competition ensues for the selection of each object property, resulting in conjunction-task activity that is intermediate to preferred and nonpreferred single-task activity. (2) Color and angle information is transmitted to rVLPFC and rDLPFC regions, between which information from both streams is shared in a bi-directional manner, resulting in enhanced conjunction-task activity. (3) In a recursive fashion, processing along the ventral and dorsal pathway between prefrontal and color-/angle-preferred regions is monitored and checked as manipulation and integration is achieved. (4) Visuospatial attentional resources are deployed to consolidate the resulting integrated representation in left parietal cortex, resulting in enhanced conjunction-task activity in this region. (5) To reduce retroactive interference between the probe stimulus presented at retrieval and the fragile contents of WM, top-down signals from the prefrontal cortex via the parietal cortex produce lower conjunction- than single-task activity in extrastriate visual areas (i.e., bilateral occipito-temporal cortex) during the more complex task. Note that components 4 and 5 are the new additions to the model based on the current data.

$P = 0.24$. This suggests that the parietal cortex region is not sensitive to difficulty/effort in the context of our experiment.

Finally, greater deactivation in default network regions for conjunction- versus single-tasks might also serve to reduce similar interference with integrated object-spatial

WM contents by nontask-relevant information in the wider environment.

CONCLUSIONS

To summarize, WM for the manipulation of both object (color) and spatial (angle) properties of two objects to produce a single integrated object is poorer than WM for the manipulation of just one object property. This conjunction-task cost in WM is relatively small compared to what would be expected if both processes occurred in true serial fashion, and suggestive therefore of a limited-capacity parallel processing model wherein concurrent manipulation of color and angle information results in an integrated representation that is lower in resolution than the representation produced on a single task. We account for this pattern of results in an extended version of the biased competition model in which competition between color- and angle-preferred regions, greater taxation of prefrontal and parietal resources, and top-down inhibition of extrastriate visual areas, all serve to produce an integrated representation of two objects that have been manipulated in WM.

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